

AUTONOMY AND THE HUMAN ELEMENT IN SPACE

EXECUTIVE SUMMARY

Report of the 1983 NASA/ASEE Summer Faculty Workshop

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# TABLE OF CONTENTS

TITLE PAGE	1
TABLE OF CONTENTS	3
LIST OF PARTICIPANTS	4
1. INTRODUCTION	7
1.1 Autonomy and Effectiveness	7
1.2 Organization of the Study and This Report	8
2. TECHNOLOGICAL AND SOCIAL ASPECTS OF THE SPACE STATION	9
2.1 Physical: Human/Machine Systems	9
Manned EVA (Extravehicular Activity)	9
Teleoperation and Telepresence	10
Robotics	11
2.2 Information: Monitoring and Control	12
Control Intelligence: Locus of Control Autonomy	12
Technology Systems: Task Performance Autonomy	13
Ground vs. Space: Locale of Control Autonomy	14
2.3 People: Humane Space Station	14
Settings and Human Performance in Space	15
Space Station Human-to-Human Communication	16
Space Station Organizational Systems	16
2.4 Human/Machine Symbiosis	17
3. CRITICAL ISSUES	19
3.1 Space Station Autonomy	19
3.2 Task Allocation and Decision Rules	19
3.3 Human/Machine Interaction	20
3.4 EVA, Telepresence, and Robotics	22
3.5 System Evolution	22
4. CONCLUSIONS AND RECOMMENDATIONS	25

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## 1. INTRODUCTION

NASA is contemplating the next logical step in the U.S. space program -- the permanent presence of humans in space. As currently envisioned, the initial system, planned for the early 1990s, will consist of manned and unmanned platforms situated primarily in low Earth orbit. The manned component will most likely be inhabited by 7-9 crew members performing a variety of tasks such as materials processing, satellite servicing, and life science experiments. The station thus has utility in scientific and commercial enterprises, in national security, and in the development of advanced space technology.

The technical foundations for this next step have been firmly established as a result of unmanned spacecraft missions to other planets, the Apollo program, and Skylab. With the shuttle, NASA inaugurates a new era of frequent flights and more routine space operations supporting a larger variety of missions. A permanently manned space system will enable NASA to expand the scope of its activities still further.

Since NASA's inception there has been an intense debate over the relative merits of manned and unmanned space systems. Despite the generally higher costs associated with manned components, astronauts have accomplished numerous essential, complex tasks in space. The unique human talent to evaluate and respond inventively to unanticipated events has been crucial in many missions, and the presence of crews has helped arouse and sustain public interest in the space program. On the other hand, the hostile orbital environment affects astronaut physiology and productivity, is dangerous, and mandates extensive support systems. Safety and cost factors require the entire station complex, both space and ground components, to be highly automated to free people from mundane operational chores.

Recent advances in computer technology, artificial intelligence (AI) and robotics have the potential to greatly extend space station operations, offering lower costs and enhanced productivity. Advanced AI techniques may help lessen dependence on ground systems, reduce mission costs, diminish complexity as perceived by the crew, increase mission lifetime and amplify mission versatility. However, technologies dealing with heavily automated, long-duration habitable spacecraft have not yet been thoroughly investigated by NASA.

A highly automated system must amalgamate the diverse capabilities of

people, machines and computers to yield an efficient system which capitalizes on unique human characteristics. The station also must have an initial design which allows evolution to a larger and more sophisticated space presence. In the early years it is likely that AI-based subsystems will be used primarily in an advisory or planning capacity. As human confidence in automated systems grows and as technology advances, machines will take on more critical and interdependent roles. The question is whether, and how much, system autonomy (self-governance) will lead to improved station effectiveness.

This executive summary report describes a study of autonomy in space and its effective use in an evolving, permanent extra-terrestrial human presence. The ten-week workshop, conducted at Stanford University during the summer of 1983 with the assistance of Ames Research Center, brought together eighteen university professors and two graduate students from institutions throughout the United States. The study was sponsored jointly by NASA and the American Society for Engineering Education as part of their continuing program of summer faculty fellowships, and was co-directed by Richard D. Johnson of NASA/Ames Research Center and by Daniel Bershader and Larry Leifer of Stanford University.

### 1.1 Autonomy and Effectiveness

Autonomy itself has no intrinsic value. It is important only insofar as it enhances or detracts from effectiveness. If component or system effectiveness improves as a result of greater autonomy, then more autonomy would be judged desirable. Conversely, increased autonomy which detracts from effectiveness is undesirable.

In the context of space habitation, exploration, and industry, autonomy refers to the network of control relationships that inevitably forms when people and machines are coupled in a common venture. Autonomy is not a property of things but rather of the relatedness of things. Autonomy thus describes the degree and nature of independence from control that an entity has with respect to any other in an organized system.

The autonomy concept is applicable to elements in any system that performs a task. These elements may be astronauts, machines, computers, sensors, or some larger or hierarchical combination of components, and each may be either a controlled object or a source of control for other elements. A three-dimensional

model of autonomy for the space station, incorporating the essential concept of independence from outside control, was developed during the workshop.

The first dimension of autonomy measures the locus of control for tasks -- that is, do humans or computers exercise the controlling intelligence, and to what degree? NASA sometimes equates autonomy with a machine system in which real-time human control is absent, or with the degree of technological development of autonomous machines and the practical applicability of these types of machines to space. These issues are an important subset of the comprehensive autonomy concept developed here.

Along a second dimension of autonomy lies the allocation of task performance to humans or machines. The more done by machines, the more "automated" the station. For instance, should humans in EVA suits or mechanical teleoperators execute a given task? Should monitoring and control functions be physically performed by people, or by largely computerized systems? How much automation or machine assistance should be inserted into work and life on a space station?

The third dimension of autonomy, locale of control, distinguishes between Earth-based and space-based control. As control moves outward into space, the station becomes increasingly autonomous from the ground. Should the site of a particular monitoring, supervisory, decision or control task be in space, on the ground, or some combination of both? To what degree should the crew be organizationally autonomous from the ground?

## 1.2 Organization of the Study and This Report

Astronauts will interact with automation and computer systems at three levels: (1) machines that work alongside people, assisting them in their tasks; (2) machines in the background that support the human presence in space; and (3) machines, in the form of the manned base station itself and indeed the whole station complex, which surround and define the human presence. These include both ground and space systems. On the basis of this perspective, section 2 discusses autonomy in human/machine systems, in monitoring and control, and in space station organizational and social factors.

Section 3 addresses critical issues which may be of particular interest and relevance to NASA project planners and managers, presented in a question-and-

answer format. These explore the dimensions of space station autonomy; human/machine interaction, task allocation and decision rules; manned EVA, telepresence, and robotics; and the evolution of an increasingly autonomous human presence in space.

The executive summary finishes with a series of specific conclusions and recommendations in section 4.

## 2. TECHNOLOGICAL AND SOCIAL ASPECTS OF THE SPACE STATION

NASA's next major manned program is likely to be an inhabited space station. This provides a framework within which to investigate the concepts of autonomy and close human/machine cooperation in space. Some issues of special interest are (1) to what degree will the space station and its crew be autonomous or independent of Earth-based control, and (2) what combination of humans and machines will be most effective for the space station? Autonomy and the human element, in the context of the station, necessarily involves difficult questions concerning the functional, physical interface between humans and machines (section 2.1), the essential nature of information-intensive monitoring and control activities (section 2.2), the tolerance limits of people and various human-social factors in space station work and life (section 2.3), and other aspects of a human/machine symbiosis in space (section 2.4).

### 2.1 Physical: Human/Machine Systems

In this section, autonomy in human/machine systems is examined for three types of systems ranging from low to high machine autonomy: manned Extravehicular Activity (EVA), teleoperation and telepresence, and robotics. The purpose here is to outline the characteristics of each technology and to make recommendations from the standpoint of autonomy and effectiveness.

#### Manned EVA (Extravehicular Activity)

Manned EVA encompasses the activities of people in space who are outside of a pressurized environment or habitat. EVA has been practiced by the United States since the Gemini program and is more common aboard the shuttle. During the lifetime of the space station, it may become necessary for EVA to become a routine operation. A heavy schedule of satellite servicing or space construction tasks may require manned EVA on an eight-hours-a-day, seven-days-a-week basis.

The main advantage of using on-site crew for EVA lies in the great versatility of human beings and in their ability to deal intelligently with unexpected situations. The two primary drawbacks to manned EVA are that (1) astronauts require a large amount of time for EVA preparation and cleanup, as well as personal time for eating, sleeping, and recreation; and (2) there are high recurring costs associated with supporting EVA crewmen. However, while telepresence and

robotics eventually will aid and augment the EVA astronaut, these cannot in the immediately foreseeable future replace all EVA functions. Thus, NASA must ensure that the necessary technology exists to support manned EVA operations.

The Extravehicular Mobility Unit (EMU), consisting of the Space Suit Assembly and the Life Support Subsystem, allows humans to work in an unpressurized environment. The EVA crewperson and the EMU together comprise a true human/machine symbiosis. The Manned Maneuvering Unit (MMU) is a propulsion unit attached to the back of the EMU to provide untethered mobility. A Manned Proximity Operations Module (POM) has been proposed as a free-flying work station which utilizes the MMU for maneuvering. The POM provides a foot restraint system which attaches to various types of surfaces and, after attachment, affords access to a large work area. POM would also help capture and maneuver satellites and transport small modules in or about the orbiter payload bay.

A real-time maintenance information retrieval system is needed to furnish the crew with sufficient information to perform any nonroutine EVA task. Currently, in part due to severe time constraints, EVA astronauts must carefully practice each step of an operation many times in ground simulators to minimize on-orbit delays and errors. With a real-time maintenance information retrieval system, astronauts could ask for and receive instructions from an onboard (or ground) database containing comprehensive information about the task at hand.

For example, to perform a satellite servicing task an astronaut might query the retrieval system verbally for the next step in the servicing operation, or for a schematic drawing of a subsystem of the satellite. Information would be delivered vocally using a voice synthesis system or visually on a head-up display. In addition, a video image of the work-site, transmitted from a small helmet-mounted CCD camera or a free-flying maneuverable television vehicle (MTV), could be provided to station or ground personnel who could then give valuable additional real-time assistance. Station operations thus become far more versatile because astronauts would only need training in generic satellite servicing tasks -- spacecraft-specific training would be unnecessary.

Neutral Buoyancy Simulation (NBS) has shown that the potential exists for work to be productively and routinely performed in space. There appears to be an instinctive adaptation to the zero-g environment which occurs after 15-25

hours of suited activity in the NBS tank, although no crewperson has yet achieved this in orbital EVA. An unrestrained worker, for instance, learns to move a high moment-of-inertia object such that it and the astronaut arrive in the desired positions simultaneously.

The ways in which people interact and assist each other at an EVA worksite need to be carefully considered. NASA flight guidelines require many operations to be accomplished by astronauts in pairs -- one person manages tools and parts while the other performs the required physical operation. It has been shown, however, that productivity is maximized when workers function independently. Lack of formal step-by-step timelines at a worksite could allow innovative methods to be tried (with due attention to flight safety), further increasing crew versatility and productivity.

#### Teleoperation and Telepresence

Teleoperation is the remote operation of a machine. This may be something as basic as recharging station batteries by simple ground command, or as complicated as controlling an on-orbit mechanical human analog. A subset of teleoperation is telepresence, wherein the remote operator performs normal human functions guided by sensory feedback simulating actual presence at the worksite.

Telepresence will be used to execute space operations which require human intelligence, control, and dexterity, and which humans cannot directly conduct due to factors such as cost or safety. For example, a sufficiently dexterous manipulator arm and vision system could possibly allow an earthbound operator to do remote lab work on the space station. A free-flying telepresence system could potentially perform satellite servicing tasks, which might be more expensive using humans in EVA, and spacecraft refueling tasks, which might be too dangerous for people. Also, EVA is limited to near-shuttle operations of six hours duration, whereas a telepresence system could function for extended times and in high altitude orbits where humans cannot work for long periods because of severe radiation hazards. Telepresence thus combines the advantages of both human and machine capabilities.

Preliminary designs for integrated space telepresence systems have been completed. In 1979, the Free-Flying Hybrid Teleoperator (FFHT) was conceptualized at the Massachusetts Institute of Technology. The FFHT is intended to be capable of propelling itself to a repair site, attaching to a structure, carrying tools

and spare parts plus a variety of sensors, diagnosing and repairing faults, and communicating with human supervisors. The teleoperator has two manipulator arms for doing work, two "anchor arms" for fastening itself to the object on which it is working, thrusters for maneuverability, communications equipment, a spare parts and stowage rack, an end-effector rack, TV cameras, and illumination sources. The Remote Orbital Servicing System (ROSS) proposed by Martin Marietta Aerospace in 1982 also would be capable of satellite servicing and would employ state-of-the-art technology. The ROSS system could fit inside the shuttle bay for transportation into space and back to Earth. Finally, the M.I.T. Beam Assembly Teleoperator (BAT) is the first integrated telepresence system designed and built for use in a simulated space environment. The BAT has performed neutral buoyancy structure assembly tests to gauge the feasibility of telepresence and to compare the performance of a working teleoperator with that of a person in an EVA pressure suit.

In the mid- and far-term, teleoperators could become sophisticated enough to conduct many station activities which previously required human dexterity and physical abilities. For example, a pair of remotely operated dexterous arms and vision systems could perform tasks a principal investigator might execute if present on the station. The teleoperation unit could prepare biological slides for analysis, conduct crystal growth experiments, and perform maintenance activities -- especially during periods when manned station modules are temporarily uninhabited. It is even possible to conceive of a module with a radically different design, one optimized for teleoperation and automated functioning through the use of dedicated non-anthropomorphic special-purpose machinery. It appears, however, that much more development is needed before this becomes a feasible scenario.

For ground-based operators, force and tactile feedback are impractical because of communication time delays. If the space station is used as a control center, satellites at the station or within direct communications range could be serviced with essentially no time delay and more delicate manipulation is feasible. However, the advantages of operating from the space station must be significant since the cost of on-orbit crew time is very high. Careful tradeoff studies could determine the types of tasks that can be performed adequately with a time delay, and those which cannot tolerate delays due to the need for rapid

sensory feedback.

Automated control will initially be implemented on simple tasks such as changing end-effectors or moving a manipulator arm to a standard position. As confidence grows and capabilities evolve, more complex tasks involving some decisionmaking will be controlled by automated supervisory systems. For example, a telepresence operator might give the high-level command "REMOVE PANEL." The supervisory control system then decomposes this command into lower level commands -- find the desired panel, determine the proper manipulator and end-effector motions to remove the panel, perform the actions, and finally stow the removed panel.

Building on previous advances, a supervisory control system could eventually perform tasks as complicated as "REPLACE COMPONENT XYZ" -- it would look up the position of the part, open the access panel, remove the module containing the component, replace the component, and return the module to its proper position. At this point the difference between autonomous operation (robotics) and supervisory control becomes blurred. When the computer on a remote device is programmed with sufficient artificial intelligence to perform appreciable planning and decisionmaking, it becomes a robot.

#### Robotics

Although the use of robots is growing rapidly in industry, robotics cannot yet play a significant role in projected near-term space station activities. However, considering the current level of research activity in the field, robots may become useful on the station in the not-too-distant future. There are two principal research goals: (1) relieving people of tasks which are boring or dangerous, and (2) expanding human capabilities, thus increasing efficiency and productivity.

A number of mechanical classes of robots may find application at or near the space station. Familiar examples of robot arms that look like human arms are the space shuttle Remote Manipulator System (RMS) and the Unimate PUMA, a widely used industrial robot. On a scale smaller than the RMS, humanoid manipulators may find application in satellite repair and servicing, space manufacturing, and station laboratory tasks.

Cylindrical manipulators are of particular interest in a cylindrical station module. A manipulator link could slide along an axial fixed rod, rotating or telescoping in a perpendicular plane. Such a manipulator could reach laboratory

or commercial work stations positioned around the inside surface of the cylinder module from a direction normal to their surface. On another part of the inside wall an interior parts carousel would enable fast end-effector changeout. Of course an entire module need not be dedicated to the manipulator -- perhaps only end or center segments of the module might be used in this manner.

Tentacle manipulators have the maneuverability of an octopus arm. They are comprised of many small links connected by joints each with multiple degrees of rotation. Such manipulators were conceived early in the history of robotics, and today at least one company manufactures and markets a tentacle manipulator, but relatively few have been built because they are mechanically challenging and have proven hard to control. One significant difficulty with terrestrial applications of tentacle manipulators is poor force delivery -- they cannot move much mass. In space this is no problem because even very large masses can be moved with small force at low acceleration.

Assembly tasks are a principal projected application for space station robots. One example is the construction of extensive space systems such as a large solar collector, which involves many relevant subtasks (e.g. material handling, fastening, subsystem assembly, inspection, repair). Besides assembly, countless space manufacturing and laboratory tasks can be performed by robotic manipulators. Many activities related to satellite servicing may also eventually lend themselves to robot application, though first implemented via manned EVA and telepresence -- such as capture and berthing of satellites for inspection, repair or modification, and fluid servicing performed either at the satellite's orbital location or back at the station.

Rather than build specialized manipulators for each of these tasks, NASA should develop a standardized Versatile Space Manufacturing Manipulator (VSMM). The VSMM would be the space station equivalent of the Unimate PUMA on Earth, a general-purpose manipulator outfitted to handle a variety of end-effectors and sensors. Developing the VSMM would be less costly than developing and space-qualifying a large number of specialized manipulators.

As technology continues to evolve, robots will play an increasingly significant role on the station and in other space ventures. Robots probably will not be applied to satellite servicing until after the year 2000, although some space manufacturing applications are foreseen

for the 1990s. This conclusion is based not only on the required technological developments, but also on the anticipated timelines for obtaining space-qualified status for new devices and systems as they emerge.

## 2.2 Information: Monitoring and Control

The space station will need a control system unlike any that has flown before. The station also requires sophisticated monitoring to assess its performance, to manipulate its system states knowledgeably under automatic control, and to detect and diagnose abnormal conditions. A larger number of subsystems are planned than for any previous spacecraft.

The space station is much like an intelligent organism, having organs and effectors such as the Environmental Control and Life Support System (ECLSS) and the Power System (PS). Much of the normal operation of these systems will be monitored and controlled by low-level devices ranging from simple feedback loops to dedicated microprocessors. These low-level monitoring and control systems are something like the peripheral nervous system in humans. The intelligence of the space system is at a higher level, an analog of the central nervous system with intellect divided between humans and computers. People set the goals of space station activity; machines help by generating and evaluating alternate choices to be presented to humans for final decision, and by diagnosing system malfunctions and recommending or effecting repairs with varying degrees of autonomy.

Station monitoring and control intelligence can be visualized as a computational hierarchy. At the lowest levels are various sensors, effectors and subsystems which mediate the bulk of station activity. Primitive monitoring and control systems reside at the next higher level. Advances in computer architecture and microprocessors will greatly expand the processing power available. Above these are the higher-level control and diagnostic systems, and at the topmost level are people accompanied by their intelligent planning tools. The highest levels require adaptive control, real-time simulation and the use of artificial intelligence technologies such as expert systems, intelligent human/machine interfaces with natural language and (possibly) learning, and supervisory control systems.

## Control Intelligence: Locus of Control Autonomy

Typical monitoring and control activities aboard the space station (and to some extent on the ground) might include (1) the ECLSS; (2) power sources, management, and distribution; (3) flight control; (4) thermal control; (5) malfunction and warning reconfiguration; (6) traffic control; (7) manipulator control; and (8) TMS (OTV) checkout and launch. In these situations, the human operator becomes involved in monitoring system equipment, process control, and the diagnosis of system malfunctions. Therefore, a computer-based process control paradigm of a supervisory nature appears most appropriate for station automation.

Some autonomy must reside in all levels of the hierarchy of a practical system. Routine, robust, small-scale tasks should be controlled in substantially autonomous small loops with little need for human intervention. Critical, fragile or large-scale operations require control at a higher level in the hierarchy, possibly with considerable human assistance. At the highest level, human supervision governs the ground-space complex. Given limited present machine intelligence capabilities, only people can serve as innovators in the autonomous system.

A recent advance in computational methods known as expert systems may provide a useful tool for high-level space station planning, monitoring, interpretation, and control functions. Expert systems operate in a manner determined by human procedures, and a user can verify that they are following human-originated rules. This verification is supplied on demand and is essential to human belief in the results.

Expert systems are just now evolving out of the research stage. They have been most successful in problem-solving applications such as medical diagnosis and electronic circuit analysis, but also hold substantial promise for providing a control mechanism where interpretation is required. As a simple example, the shuttle has five flight computers, each constantly making judgments as to whether it and the other four are operating correctly. This judgment is displayed as a 5x5 pattern of lights on the shuttle command console. Three of the computers are in use at any one time. Currently, an astronaut must interpret the display to decide which computers should be used. An expert system could relieve humans of this task rather easily.

Expert systems are a promising methodology for automating much of the de-

cision process regarding fault diagnosis and correction procedures. An even more complex concern is the ground monitoring and control of space missions. Currently, many personnel are needed -- about 400 people every shift for the shuttle. On Skylab, seven people per shift were required just to control power load balancing. This type of control could be partially handled using a mixed-initiative expert system able to respond to data on an exception basis. Most current expert systems collect data from a broad range of sources, some not particularly relevant to the solution of the problem at hand. An exception-driven, mixed-initiative expert system would respond to information passed to it of an exceptional nature, informing the crew, for example, "CABIN PRESSURE REDUCED TO 5 PSI" and then initiating requests for additional data that might be relevant. Further research is needed into the structure and nature of mixed-initiative expert systems.

Natural language is what people use to communicate with other people, usually with the narrow technical meaning of a written or spoken language such as English. The specific goal of an AI-based natural language system aboard the space station is to enhance human-to-machine and machine-to-human communications. The astronaut may wish to tell the machine to do something, or the machine need to provide information to someone, both of which are best accomplished in a natural language format. For instance, the system could respond to the spoken command "ROTATE INSTRUMENT POD NINETY DEGREES" or it could initiate the message "FIRE IN STORAGE LOCKER A12."

Database access via natural language is also desirable. It is very important that the data management system for the space station be planned in the very beginning stages of space station design, not instituted as an afterthought. NASA should consider developing a computer simulation and data management system for the space station, implemented end-to-end -- from original mission definition to spacecraft design, manufacture, test, integration, launch, on-orbit checkout, nominal operations, spacecraft modifications, and fault diagnosis and handling. Such a system would enhance mission supervision effectiveness and reduce documentation costs. An opportunity also clearly exists for the application of computer-aided engineering. Space station information is already growing and should become part of a complete knowledge base that can be used throughout the station lifetime, from inception through maturation. As such, it must be

guided not only by the essential standards for compatibility (e.g., standard character codes) but also by the principles of knowledge base construction that are being discovered, tested, and formulated in the course of AI research today.

#### Technology Systems: Task Performance Autonomy

Sensors respond to physical stimulus and transmit a resulting signal containing information about the stimulus to a controller or operator. The machine implementation of the five human senses is not a central problem. Rather, the interpretation and utilization of sensed information is the principal research area restricting space station task performance autonomy. In robotic and telepresence system design many "senses" not known to be possessed by humans are available, such as particle radiation detection and infrared wavelength imaging. Sensor technology allows tasks (normally requiring the presence of humans in space) either to be performed from the ground or to be fully automated. Sensing plus appropriate interpretation permits the extension of human capabilities to the performance of tasks which would otherwise not be possible.

Displays convey information. Humans perform poorly at monitoring data-intensive displays, so this task is an excellent candidate for automation. High-level displays should be standardized. Adoption of stimulus-response and multi-display compatibility should greatly reduce operator errors. Also, research and development is needed in zero-g workload measurement and in establishing criteria for acceptable workloads as a function of time and stress.

Controls, like displays, must facilitate communication between humans and machines. The primary interface between the human operator and the space station will most likely be a vide screen, and the primary means of data input will be touchscreens and joystick/mouse pointing devices. The use of a menu select system could aid in reducing the number of discrete controls (and displays) on the space station, but a high degree of robustness and redundancy is essential to maintain user confidence. Speech recognition or voice entry is another means of data entry and it is also potentially a means of controlling human/machine systems such as the MMU. Another class of control technology is biocybernetics -- in particular, the use of electrical potentials from the brain. This technique is still in the initial stages of research and much work remains to be done

before it becomes a viable alternative.

The space station possesses a number of hardware and software components essential to its operation. Most important for establishing autonomy are sensors and controllers. Sensors measure system states or variables, providing signals for front-end data handling devices which produce digital information for automatic control of manipulated variables, thereby regulating the station. Controllers are envisioned to be microprocessor-based digital computers, more than a hundred of them on the manned platform alone. These will be responsible for sustaining the environment within a stringent set of tolerances; distributing power to devices based on equipment need and power system potential; monitoring adjacent space and maintaining a fleet of manned and unmanned platforms. Controllers must be robust, adaptive and multivariable, with redundancy, adaptability, reliability and maintainability.

Computer network buses will permit common access to data by any controller or other device directly or indirectly connected to the network, with the added benefit that individual failure of controllers might be automatically corrected. A multi-computer-based network with multi-accessible channels and modules for distributed controls, interactive supervisor consoles and automatic ground communications forms the fundamental nervous system for the intelligent space station, using, quite possibly, an existing commercial configuration.

#### Ground vs. Space: Locale of Control Autonomy

Some monitoring and control functions, such as space station system modelling, are best performed on the ground. The initial station monitor/control system will have been tested and modelled prior to its flight, but this must necessarily be incomplete since the overall system is essentially unique. In addition, the monitor/control system requires constant updating due to wear, failure and replacement of parts, and due to station component reconfiguration and changing objectives. A revised version of the current working model must be periodically transmitted to station supervisory computers. However, on the ground there is greater human support available, computer systems have larger capacity and are less expensive, and the time allowed for model upgrades can be relatively long. The proper locale for this task is the ground.

One task probably best left exclusively for space-based control is station stowage and inventory management. Skylab

astronauts frequently reported misplacement of stowed items from their original locations. Items removed from one compartment were sometimes placed into a nearby but different stowage locker, often under pressure of time and without telling anyone. An onboard computerized stowage and inventory management system, possibly voice-activated, could handle this problem -- an excellent opportunity for human/machine cooperation.

A few monitoring and control tasks are best shared by ground and space controllers. For example, fleet management requires detailed knowledge of relative separations, altitudes, sizes, masses, orbital rates and attitudes of each station component, but this information need not be processed rapidly and normally it is of little consequence that tracking is lost over part of an orbit. Since on-orbit time is valuable it appears advantageous to monitor the fleet using a large ground computer. However, control prerogatives such as station reboost should be initiated from space since the station is most seriously affected by the action. Reboost should not occur while local EVA, teleoperation, or gravity- or contamination-sensitive experiments are in progress; it can be scheduled well in advance and the space station and ground crews notified for concurrence. Manned modules can also maintain direct communication and radar contact with other nearby station components to avoid collisions or to effect rendezvous as required.

The above are examples of the many types of locale of control decisions. A few rules for making such decisions are suggested in section 3.2.

## 2.3 People: Humane Space Station

In the manned component of the space station complex, people varying in training and disposition, and machines varying in capability and connectedness, reside together in what is essentially a mechanically supported ecology. In a broader sense, the real boundaries of the station are not the exterior surfaces of metal, silicon and exotic materials but the organization of individuals, groups and institutions who support the work in space and who have a stake in what is done there and how. Such factors as human and machine procedures, the settings in which people work and live, the management of communication with clients on Earth, motives and goals of various entities, and work management policies all materially impact what can be accom-

plished on the station, and hence the level of human autonomy which provides maximum effectiveness.

There are three major areas of concern:

1. Physical Setting -- the intriguing challenge of designing the physical and perceptual layout of station environments for optimum integration with the behavioral needs of the astronauts; conversely, how to avoid thoughtless early design decisions which could hinder effective human action.

2. Communications Methodology -- establishing communications arrangements for a responsive, coherent station operation.

3. Organizational Factors -- how best to organize for working in a small, heavily automated, distant environment; also, issues of desirable managerial philosophies for a space station of the 1990s and beyond.

#### Settings and Human Performance in Space

Settings and behavior are inextricably linked -- the behavior a person exhibits is a function of both who and where he is. Space station setting factors will directly affect human performance, well beyond mere aesthetics or even physiological requirements. Settings should be intentionally designed to enable effective human performance and not just basic survival.

The first and most often recognized dimension of settings is the physical space itself. The human form is not as well-adapted to space as it is to Earth, so the setting in which the astronaut works and lives must accommodate the difference. The height of work surfaces, the location of controls and displays, even the placement of foot restraints and handholds need to be adapted to the human zero-g posture.

The ability to spatially orient inside the station is a basic requirement for living in space, in order to avoid, for instance, visual inversion illusions which can occur sporadically during a flight. Vertical referencing is the sense of up and down. In free fall, this status information is no longer available from human gravity sensing organs so another source is substituted -- primarily visual, conforming to the geometry of the spacecraft cabin. However, the requirement of a visually appropriate interior reference system does not mandate a simple planar arrangement of furniture, lighting and workstations. With the small habitable volume available, what

would otherwise be unused space near the "ceiling" should be made functional for living and work activities. This can be accomplished while maintaining an artificially-induced perceptual vertical.

A cognitive image is a mental map of the local environment, the internalized representation of the external world. Because of the small habitable volume, it will be important that the crew's mental maps be composed of as many distinct images as possible. For example, the workplace and the personal place should be in different locations and actually appear different in terms of surface finishes, lighting, etc. This gives the sense of having moved farther from one place to another, by substituting perceptual quality distance for actual physical distance. Also, it is crucial that station personnel be able to find their way through the station in an emergency. The station interior should be color- and tactile-coded so that even under the most debilitating conditions personnel know not only where they are, but how they are oriented and where any other location on the station is with respect to them.

Social and cultural groupings are powerful determinants of appropriate or acceptable behavior. A space station with mixed crew cultures presents the potential for misinterpretation of behavior. Setting interiors should be flexible and adaptable enough to accommodate a range of potential crew cultures and their accompanying expectations regarding privacy, proxemic distance, and so forth.

The temporal dimension is the most easily overlooked setting factor. Behaviors occur not only in physical locations but also at specific times, and purposeful behaviors are typically joined to form patterned activities over time. These activities are often composed of preparatory behaviors which anticipate an action, performance behaviors, and follow-up behaviors to disengage from or clean up after the performance behaviors. The station must be designed to accommodate patterned sequential (distinct) behaviors which may have different physical setting requirements.

If people are subjected to programmed settings and behaviors solely to reduce system costs or complexity, then some of the distinction between a human and a purely machine presence on the space station may be lost. Inflexible designs which lock people into "approved" ways of doing things diminish the advantages of a manned presence because unique human capabilities are underutilized.

### Space Station Human-to-Human Communication

Human-to-human communication between ground and space will reflect the nature and degree of station autonomy. As the locus of control for space missions moves from Earth to space (and as onboard expert systems are developed to replace ground personnel), fewer contacts are needed between the station crew and operational personnel on the ground. However, the number and quality of ground-station links might actually grow as the number of commercial, scientific and other users increases.

The availability of a "call home" social support network may be critical in long-term missions. Tapping into the current satellite-based news/entertainment networks could help keep the crew in touch with Earth culture. Because proximity represents a powerful mediator of intimacy and attraction, the broadest possible bandwidth of communication between Earth and station is advisable. Multiple direct-access communication channels should be considered for human-to-human ground-to-space contact, a marked departure from the existing highly controlled access.

In addition to facilitating the accomplishment of many tasks, a good onboard communication environment can foster feelings of group solidarity. Equally important is the ability to distance oneself from others when privacy or solitude is desired. New means of person-to-person communication (e.g., electronic mail, voice/image storage and retrieval systems) need to be explored as supplements to face-to-face communication. To prevent information overflow, an intelligent communication network should be developed that recognizes priority inputs for queuing purposes. To provide the crew with maximum time flexibility, the majority of uplinked messages should be of the personalized, store-and-forward variety.

To handle parallel message input it is recommended that multiple mixed-media workstations be incorporated into space station design -- at least one terminal per crew member. These workstations might be compact portable units similar to present-day personal computers. These could (1) double as backup display terminals for onboard monitoring and control functions, (2) serve as word processing stations for personal/scientific log-keeping and letter writing, (3) supply access to audio, video and text-oriented databases used for onboard education, training and recreation, and (4) allow the display of expert system

output in the context of person-to-person teleconferencing. Multiple terminals are essential because they are likely to be used heavily both during and after work hours and because they could be located in or moved to areas providing visual and auditory privacy such as crew members' personal quarters.

### Space Station Organizational Systems

Management and organizational systems are subject to design choices much like physical and technological factors, yet organizations often fail to recognize the opportunity. Instead, design emerges by default, rarely optimum for achieving organizational objectives. NASA should take full advantage of the flexible and creative qualities of its astronauts as decisions are made regarding human/machine divisions of labor and regarding the ability of station personnel to self-manage their operations, independent from ground control.

Technology can have considerable impact on organizational design, either supporting or diminishing autonomy. Once an organizational design concept has been established, a combined socio-technical system can be created to facilitate the desired order. Automation, for example, can free humans from tedious and routine work, thus increasing human autonomy. Equipment that will be used, maintained or monitored by people should be analyzed to determine the probable impact on human behavior in the space station social organization. Human factors engineers with sociological and organizational training should be sought out and added to the design team.

What is the appropriate degree of control of ground personnel over station crewmembers? In recent years, the trend in American management has been towards greater decentralization -- more autonomy -- among organizational subunits. Effectiveness gains appear through (1) closer attention to problem-solving and decisionmaking information, (2) higher motivation, (3) significant improvement in quality, (4) greater adaptability, (5) less surveillance (lighter supervision, smaller staffs, less overhead), and (6) faster and more creative decisions.

While most of NASA's past experience with ground/crew relationships has been satisfactory, occasional behavioral malfunctions already have occurred as a result of stressful situations. Particularly in missions lasting many months, greater autonomy from ground control is recommended. Crew scheduling is a case in point. Scheduling has traditionally been done by ground operations because of the complexity of the task. The result

of the scheduling process is a daily work activity timeline that is sent up to the crew each morning — with the potential for insensitivity to human foibles and to real-time demands of the on-orbit situation. Fortunately, it is now feasible to use an expert system work activity planner which can interact with the crew, allowing them to prepare their own timeline.

## 2.4 Human/Machine Symbiosis

The decision to automate certain aspects of space station operations demands a careful consideration of potential human/machine relationships, including function allocation and the element of mutual trust. The decision to use a machine or tool depends on numerous factors such as availability and appropriateness, initial costs, compatibility with existing systems, and other context-dependent factors. Few makeshift tools or exogenous resources will be available, so great selectivity must be exercised.

But the concept of symbiosis goes beyond mere tool-use. Symbiosis generally refers to a mutually beneficial union or association of two dissimilar organisms or entities. Past space missions have often been termed "manned" or "unmanned," but the apparent dichotomy is illusory. The space effort has involved an ever-deepening symbiosis between people and machines. "Unmanned" missions have been manned by ground personnel -- if only in the teleoperated mode -- and past "manned" programs such as Apollo and Skylab could not have succeeded without heavy reliance on automated systems. In the context of the space station, symbiosis implies an even more sophisticated and comprehensive marriage of unique human and machine characteristics, with each regarded as integral components of a single symbiotic system from the very first stages of conceptualization and design. Decision rules must be formulated to determine how human/machine functions can best be structured to optimize station effectiveness.

At the present time there are few recognized systematic methodologies available to guide the allocation of functions. Von Tiesenhausen (NASA TM-82510, 1982) has catalogued various human and machine capabilities to aid in allocation. For instance, humans surpass machines in their ability to perceive patterns and generalize about them, to detect signals in a high noise environment, to store large amounts of information for long periods of time, to remember relevant facts at the

appropriate time, to use judgment, to improvise and adopt flexible procedures, to handle low-probability alternatives, to arrive at new and completely different solutions to problems, to profit from experience, to perform when overloaded, and to reason inductively. On the other hand, machines best contribute to the symbiosis in monitoring, in the performance of routine, repetitive, and precise tasks, in storing and recalling large amounts of precise data for short periods of time, and in their ability to compute, to respond quickly to control signals, to handle highly complex operations (i.e., doing many different things at the same time), to reason deductively, to ignore extraneous factors, and to reduce cost in many cases (see section 3.2).

A more formal approach to function allocation which applies both to station crew and to ground support personnel, and which may be particularly applicable in the early stages of space station development and automation, is the use of task analysis. Briefly, task analysis defines for each task the inputs needed and the outputs to be achieved. The analysis may be used to determine the information and control requirements of a task prior to the selection of equipment to be operated by the human; to determine skill and knowledge requirements; to estimate errors; to predict workload and scheduling; and to provide time information.

True symbiosis requires mutual trust. When should a human trust a machine, and should the trust ever be complete? If people must gain trust incrementally, or through reputation, with the large range of devices they may encounter, this trust will be gained: (1) if they are generally disposed to the value of using machines (this trust may be qualified by cues from specific machines, or knowledge suggesting that some kinds are more trustworthy than others); (2) if initial experiences with the machine are safe, efficient, pleasant, and seem to accomplish what was intended from its use in an acceptable way; (3) if people are clearly gaining benefits from its use; (4) to the extent that the machine, though occasionally unreliable or quirky, permits easy recovery from mistakes, losses or hangups; (5) if people understand how the machine works; and (6) if the machine is responsive in giving indication of internal or remote states, and these indicators are generally valid.

The question of machine "trust" of humans also enters the design of critical systems. In the past, people have placed

faith in stable structures and even somewhat risky ones such as high-spirited horses, rope bridges, and re-entry vehicles. We already design a kind of "system trust" into our computer systems -- a machine trusts only those persons with correct identification and password, without which interaction ceases and alarms may even be sounded. Levels of machine trust of humans are also reflected in access to sensitive areas of confidential information and internal systems codes for privileged users. If machines are to make judgements about how well to trust individual people, as contrasted with mere design biases, then those who interact with the machine must be identifiable individually, and either external information on their expertise fed in or some kind of usage statistics accumulated.

### 3. CRITICAL ISSUES

Certain questions repeatedly arise in program planning and advocacy. The following critical questions represent current concerns and issues related to human/machine operations in conjunction with a space station. These are categorized by major functional relationships between human and machine in a question-and-answer format.

#### 3.1 Space Station Autonomy

Question 1. What is autonomy in the context of the space station? How should autonomy be viewed in this context?

The generic meaning of autonomy is independence or freedom from outside control. Examples of space station autonomy might include station independence from ground control, machine independence from human control, crew freedom from unnecessary tasks, free-flyers functioning independently, or the end-effectors of a teleoperator system removing bolts during satellite repair without a human presence.

The workshop model of autonomy includes three dimensions (see section 1.1). The first dimension is locus of control -- where does the system control intelligence reside? A machine which is self-controlled has a high degree of control autonomy, whereas a machine controlled by a human has low autonomy. Note that the object of autonomy is the machine itself and not the human/machine system. The second dimension addresses physical task performance. If the task is done almost entirely by a machine, then the machine has high autonomy. The third dimension is locale of control. Humans, machines, or human/machine space systems that are relatively free of control from the ground have high autonomy. An object or system controlled more directly from Earth is less autonomous.

Question 2. In the 1990s, how autonomously (from the ground organization and system) can the space station operate?

Some long-term unmanned missions have not required the extensive and expensive mission control personnel of the manned flights. The space station, viewed as a continuous manned mission, should display more of the attributes of these long-term unmanned activities. The station will become more autonomous from ground-based human supervision. Control and decisionmaking will shift increasing-

ly to the space station. Much of the monitoring currently done by people can be highly automated. Earth-based human experts will be available for backup if unexpected problems arise.

The early space station may not be significantly more autonomous from the ground than present manned systems, but over time there will be a gradual shift in locale of control. By the mid- to late-1990s, there could be substantial space station autonomy as confidence in automated systems grows with increasing use. NASA should try to automate as much as possible. Some suggested decision rules for re-allocating task locale from ground to space include: (1) Can the task be performed only in space with the required reliability? (2) Is the performance in space of the task necessary for the well-being of the crew? (3) Is the immediate judgment of the space crew necessary for the task? (4) Is it less expensive to do the task in space with the required reliability?

#### 3.2 Task Allocation and Decision Rules

Question 3. What is the nature of an on-board task that determines whether it is appropriate for automation? What type of tasks should be allocated to humans? What combinations of humans and machines will be most effective?

At the present time there is no good systematic approach available for the allocation of functions to machine and human operators, let alone between astronauts and automated systems. Tables of tasks best performed by humans or machines have been compiled, but these are incomplete. Some monitoring and control systems can be automated with current technology. Tasks requiring complex levels of decisionmaking probably will not be automated until the end of the century; functions requiring judgment and interpretation of unexpected events will be automated only in the long-term. Tasks demanding human-like dexterity will be difficult to automate with current technology unless they are repetitive and very limited in their requirements for fine manipulation.

In general, machines tend to be quite reliable but lack flexibility while humans tend to be less reliable than machines but far more flexible. If the subtasks remaining after automation (such as watching monitors) are more boring than the original task, then it is better not to automate and to let astronauts perform the task in its entirety. Humans have the ability to supervise and control

and should not have to perform menial subtasks which subordinate people to machines. An effective human/machine combination is teleoperation or telepresence systems. In these systems the human remains in a safe environment and performs tasks which may otherwise: (1) be unsafe, (2) require strength beyond human capability, or (3) require prohibitively expensive EVA or vehicle life support systems or development of an autonomous machine beyond the reach of current technology. Present-day end-effectors are barely adequate but aggressive development in this area seems more practical in the near-term than pursuing a purely AI-based approach.

Question 4. What are the decision rules for allocating functions between humans and automated systems, whether in space or on the ground?

One approach to devising decision rules is to create an expert system such as SSTAAMMER (Space Station Task Allocation Among Men and Machines, an Expert Reasoner), a software package developed during this study. An expert system is an artificial intelligence approach to decisionmaking, which builds up evidence for choices by asking users questions based on an established set of rules. The particular trial rule set for SSTAAMMER was derived from several sources, including a study of human/machine task allocation by Von Tiesenhausen (NASA TM-82510, 1982) and suggestions by Faculty Fellows and other workshop participants. This set is exemplary and should not be regarded as definitive, exhaustive or conclusive.

Strong evidence for the decision to automate may exist (1) if the task requires perceptual abilities outside the range of human limits; (2) if the task involves safety or health risks outside tolerable limits for humans; (3) if the task requires computing ability; (4) if the task entails detection of infrequent or rare events; and (5) if the task requires continuous monitoring of systems. Weaker evidence for favoring automation arises (1) if it is technically feasible to automate the task; (2) if it is economically feasible to automate the task; (3) if the task involves storing and recalling large amounts of precise data for short periods of time; (4) if the task involves routine repetitive precise tasks; (5) if the task requires regularly an attention span of more than 20 minutes; and (6) if humans don't like to do the task.

Strong evidence favoring humans for

a task may exist (1) if the task requires deductive reasoning ability; (2) if humans like to do the task; (3) if the task requires the ability to arrive at new and completely different solutions to problems; (4) if the task requires the ability to detect signals in high noise environments; (5) if the task requires ability to use judgment; and (6) if the task entails many unexpected or unpredictable events. Weaker evidence for using people may arise (1) if the task requires EVA; (2) if the task requires the ability to profit from experience; and (3) if the task cannot easily be decomposed into a series of preset procedures.

Question 5. What are the decision rules for determining whether a function can be performed better in space or on the ground?

Allocation of activities between ground and space may also be discussed in terms of possible decision rules for an expert system (see Questions 4 and 2).

Strong evidence for allocating a task to be done in space exists (1) if the task requires the space environment; (2) if time delays cannot be tolerated; (3) if the task requires the physical response of the crew; or (4) if the task involves crew leadership, requiring a common sense of sharing a stake in the station situation. Weaker evidence favoring space arises if the task can be done less expensively in space.

Strong evidence favoring ground allocation may exist (1) if the task does not require the immediate action of the crew or (2) if large space or heavy machinery is needed. Weaker evidence for performing the task on the ground may arise if the task costs less when performed on the ground.

### 3.3 Human/Machine Interaction

Question 6. What is the astronaut's role with respect to onboard autonomous subsystems? In what operational modes does man serve best?

The astronaut will function as supervisor or manager and must understand basic system behavior, diagnose faults, and repair or replace faulty components. However, many subsystems will be self-contained and will operate independently. With automated space station monitoring, subsystem abnormalities will cause a higher-level system (machine or human) to be alerted. Using fault-tolerant comput-

ing and redundant systems, many faults can be handled without human intervention. If the troubleshooting procedure for the detected fault is well-specified, then the computer should complete as many of the steps as possible before alerting the crew. This avoids the inefficient current practice of human review and execution of an entire troubleshooting procedure which is largely routine. Of course, if a critical system must be shut down or a redundant system started up, humans should be consulted or informed so that there is an opportunity to approve or disapprove the action.

Of course there are many faults which are unanticipated or for which no simple step-by-step procedure can be written. In these cases, helps, hints and operational information should be provided by the station data management and information retrieval systems (section 2.1) but the human must make the decisions, perform the troubleshooting and make the repair. Ideally, the crew could still repair faults in critical systems, such as communications, autonomously.

Question 7. What are the management principles for operation of autonomous subsystems, particularly as a function of machine intelligence?

They are largely unknown. Intelligent systems are currently most adept at dealing with symbols rather than material objects, and can work with sets of rules as in expert systems. If the operation of the subsystem, which may include fault detection and resolution, can be reduced to a specific set of conditions and remedial actions, then the system can be managed by machine intelligence. If the system requires changes in operation based on unexpected or unpredictable results, then state-of-the-art AI techniques are inadequate.

Current expert systems produce very impressive results, but these packages generally are used by people whose expertise is comparable to that embodied in the software. Expert operators are required, both to ensure the "common sense" of results and to modify the system's rules as new expert knowledge accumulates (although learning and automated theory formation are reasonable goals for the future). For the initial station design, prudence suggests limiting deployment of expert systems to domains in which they are known to work, such as monitoring and fault diagnosis of power systems or interactive real-time crew scheduling. As other working systems are demonstrated

and evaluated they should be added to the evolving space station. Caution is advised, but it should be possible to identify potential domains where an expert system might be suitable for future station implementation.

Question 8. How does one determine when human intervention is required? What are the principles which determine how to provide status information to the human? How can unsafe human interventions be prevented?

Humans should be involved in the control of an action or decision which is irrevocable or which significantly affects another system. The level of action to be taken and the seriousness of the event requiring action determines how status information will be presented. A major failure should attract attention immediately, probably through both audio and visual alarms. Additional information describing the cause and nature of the failure should be displayed on a CRT. But printed warning messages are less effective than using both audio (e.g., voice or sound) and visual signals (e.g., a flashing light). Minor events should activate a small visual indicator or log a message for later review.

The two main concerns with unsafe human intervention are that (1) an unauthorized person might interact with the system, and (2) an authorized person could make a mistake adversely affecting the system or other systems. Fail-safe interlocks and passwords can prevent unauthorized action. Good training and a basic understanding of the systems would provide significant assurance against mistakes. Other steps can also be taken. For example, if an action could cause major damage, then the assent of more than one person might be required -- perhaps that of a crew member and another person on the ground. Computers could perform a contingency analysis for the crew, or request that crucial commands be repeated, prior to taking action.

Question 9. What new skills do people need in dealing with autonomous subsystems? What skills (organizational, personal, and physical) need further development?

The needed skills are similar to those presently required for the astronaut program. People who deal with autonomous subsystems must be comfortable working with automation technology and must thoroughly understand the displays

and information presented by station systems. This requires intensive training and an ability to maintain high levels of familiarity with the technology. Strong decisionmaking skills are essential, such as when serious component failures or other stressful situations necessitate rapid assessment of the accuracy of autonomous subsystem feedback -- especially if this information conflicts with intuition or common sense.

It is possible to envision an "expert power based" organizational system for the space station, in which authority resides with the person who is expert or has knowledge related to a given situation, rather than a commander or pilot. The workshop group largely rejected this approach, at least in the case of stressful or emergency situations. Even the early American navy had sailing masters to navigate and maneuver the ship, and gunnery officers whose job was the care and feeding of very primitive and temperamental cannons. In each case the person in command was dependent on technical specialists, yet this did not affect the nature of command authority. It seems unlikely that electronics will much alter this situation.

Organizational and personal skills needing development are the ability to live (and thrive) in a cramped, fragile, artificial habitat located in a hostile environment from which immediate escape is impossible; and the ability to design and operate decentralized social systems (i.e., greater autonomy for organizational subunits), multimode computer-augmented interpersonal communications networks, and evolutionary human/machine systems.

### 3.4 EVA, Telepresence, and Robotics

Question 10. What are the decision rules which apply to extravehicular operations? What advancements in technology are required to shift the task allocation?

Decision rules which might be used in an expert system (see Question 4) were identified during the workshop. There is strong evidence favoring manned EVA (1) if the task can be done with safety or (2) if the task requires working with non-standard fasteners and tools; and weaker evidence (1) if the task cannot be reduced to a series of preset procedures or (2) if the task requires sensitivity to a wide variety of stimuli. There is strong evidence that a human/machine system should perform the EVA (1) if the task is dangerous or (2) if the task is repetitive and requires limited dexterity; and weaker evidence (1) if the task

must be done immediately or (2) if the task requires continuous work of 4 hours or more.

Technologically the primary components of an early telepresence system are available but the integration of these components is necessary in order to provide an operational system in the near future. Ground-based telepresence has limited application because of the delay problem. A larger variety of end-effectors with greater effectiveness and dexterity must be developed, and tactile sensors must be improved. However, standardization of connectors, fasteners, attachment methods, module configuration and tools could accelerate the use of telepresence as an operational system even without the aforementioned advances.

Robotics will take advantage of gains in telepresence systems, but major significant improvements must be made in artificial intelligence systems before robots will become an effective part of the space station system. Limited use of supervisory control should be possible in the 1990s.

Question 11. How can the man/machine mix be optimized for extra-station activity? What evaluation criteria apply?

Manned EVA is useful in many situations because intelligence and flexibility are important human characteristics. However, the space environment places severe restrictions on human activities (e.g., reduced dexterity, short operational time, bulky life support systems). With the limited abilities of available intelligent machines, the use of teleoperated systems may provide an effective and, with foreseeable technology, near optimal human/machine mix. With the astronaut as operator, telepresence employs human judgment and manipulative skills, takes advantage of machine durability and mechanical performance, and can incorporate autonomous robotic technology as it becomes available.

As human/machine capabilities are developed it may be useful to use a weighting function in the decision process which includes the importance of the task, the effectiveness of the human/machine system, and the cost to support the system.

### 3.5 System Evolution

Question 12. What is a feasible evolution of human/machine systems in space over the next 20-30 years? How will the human/machine interaction change over

time? What is the role of people in human/machine systems as these systems evolve with technological advances?

When the space station is first launched in the early 1990s, people will still play the dominant role in almost all human/machine systems. Manned EVA will be used extensively in construction and satellite servicing. Mechanical manipulators with limited dexterity and sensory feedback also will be employed. These will be teleoperators or telepresence devices with human controllers and decisionmakers. Monitoring will be done by computers of limited "intelligence" (e.g., fault-tolerant systems), but under human supervision. Much of the decisionmaking control will shift from ground to space station and the crew will receive intelligent assistance from on-board computers. The major computers for monitoring and mission operations will remain on the ground together with a limited number of operators and experts.

This mode of operation will change dramatically over the following 20 years. Information will become much more available and cheaper, just as most other resources will become more expensive. The human/machine interface will become more permeable, allowing easier transfer of information. This process is already underway in terminal design, relational database organization, attempts at natural language front ends, expert systems, and head-up displays.

It is unknown how intelligent machines can become. The conservative assumption is that problems in developing basic AI theory will prove as intractable as those of turbulent flow, but, to extend the analogy, that some very useful systems will be flown nevertheless. In all likelihood, advances in AI will allow truly intelligent machines to exist. Highly-developed sensory capabilities will extend the uses of autonomous robots. Intelligent assistants and monitoring systems will be created and installed on the space station. Nearly all space system activities ultimately may be controlled from an expanded space station.

The use of autonomous, intelligent machines will not reduce the amount of work that humans do but rather will permit the effective performance of an ever-increasing number of more complex and productive tasks.



#### 4. CONCLUSIONS AND RECOMMENDATIONS

The following are general conclusions suggested by the results of the present study:

1. Machines will not replace humans in space. Rather, they will free us for more productive endeavors. People and machines in space will demonstrate new types of interactions and will thrive, not just survive. The people and machines must be viewed as an integral system from the first stages of conceptualization and design.

2. Artificial intelligence systems will not have a major impact on the initial space station design for the early 1990s. There are expert systems that can be employed in specific areas but it will take at least another 5-10 years before highly autonomous intelligent machines become available. An evolutionary station should be designed with this future possibility in mind.

3. Two areas of human/machine interaction appear most promising: (a) Using computers for monitoring with humans serving in a supervisory capacity, and (b) direct interaction in the form of teleoperation and telepresence. No major technological breakthroughs are necessary to develop effective teleoperation systems. These systems eliminate the near-term need for extensive intelligent AI systems, and the development of superior end-effectors will provide exceptional physical capability. Furthermore, as artificial intelligence systems emerge, the advances which have been made in teleoperator systems can be used to create more efficient and effective robots.

4. Sophisticated monitoring systems can be developed to sharply reduce ground personnel requirements. However, use of these systems will not increase ground/space station autonomy because monitor computers will be located on the ground so they can be improved and developed as technology advances. Later, though, most of the human control will shift to the space station.

5. Ultimately, the space station is the gateway to colonization and the forerunner to permanent space colonies, a launching platform to other planets and a stepping stone to the stars.

We recommend the following to NASA:

1. Major effort and funding should go into the development of manned EVA, teleoperator/telepresence and robot systems. NASA should develop EVA suits, tools, and capabilities for near-term use; invest in telepresence and AI in the immediate future for near- and mid-term use; and invest in robotics for mid- and long-term use.

2. Using the latest technology, high-level monitoring systems should be established on the ground, with onboard microcomputers maintaining the normal operation of many station systems and taking over many routine decisions formerly made by humans. Astronauts must retain ultimate authority, making the highest-level decisions of which machines are incapable. Databases should be developed with eventual AI uses in mind, and accessible by all users. One or more computer networks should be employed on board the space station, enabling critical functions to be separated from scientific and other uses. Every effort should be made to take advantage of the capabilities of commercial systems, particularly in the areas of computer hardware and software development, natural language and expert systems.

3. To counteract the psychological and social negatives of living and working in a highly automated, relatively isolated artificial environment, the space station should be designed from the outset with extra-terrestrial setting factors, communications factors, and organizational factors in mind. Interdisciplinary teams should address problems of work and setting design for human/machine interaction. The station should be viewed as a facility instead of a flight. NASA should encourage an up-to-date examination of issues and findings in social sciences research of possible relevance both to space station organizational and physical design and to a long-term human presence in space.

